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Meredith Greer
Bates College, mgreer@bates.edu

Olcay Akman

Timothy D Comar

Daniel Hrozencik

Jonathan E Rubin

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Paying Our Dues: The Role of Professional Societies in the Evolution of Mathematical Biology Education

Meredith L. Greer · Olcay Akman · Timothy D. Comar · Daniel Hrozencik · Jonathan E. Rubin

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Abstract Mathematical biology education provides key foundational underpinnings for the scholarly work of mathematical biology. Professional societies support such education efforts via funding, public speaking opportunities, web presence, publishing, workshops, prizes, opportunities to discuss curriculum design, and support of mentorship and other means of sustained communication among communities of scholars. Such programs have been critical to the broad expansion of the range and visibility of research and educational activities in mathematical biology. We review these efforts, past and present, across multiple societies – the Society for Mathematical Biology (SMB), the Symposium on Biomathematics and Ecology Education and Research (BEER), the Mathematical Association of America (MAA), and the Society for Industrial and Applied Mathematics (SIAM). We then proceed to suggest ways that professional societies can serve as advocates and community builders for mathematical biologists at all levels, noting that education continues throughout a career and also emphasizing the value of educating new generations of students. Our suggestions include collecting and disseminating data related

M. Greer (Corresponding Author)
Department of Mathematics, Bates College, Lewiston ME, USA, ORCID: 0000-0002-9543-4498
E-mail: mgreer@bates.edu

O. Akman
Center for Collaborative Studies in Mathematical Biology, Illinois State University, Normal IL, USA, oakman@ilstu.edu, 309.438.7980

T.D. Comar
Department of Mathematics, Benedictine University, Lisle IL, USA, tcomar@ben.edu

D. Hrocenzik
Department of Mathematics and Computer Science, Chicago State University, Chicago IL, USA, dhrozenc@csu.edu, 773-95-2228

J.E. Rubin
Department of Mathematics, University of Pittsburgh, Pittsburgh PA, USA, jonrubin@pitt.edu, ORCID: 0000-0002-1513-1551

to biomath education; developing and maintaining mentoring systems and research communities; and providing incentives and visibility for educational efforts within mathematical biology.

Keywords professional societies · mathematical biology · education · interdisciplinary · curriculum · conferences · publishing · mentoring · awards

1 Introduction

Professional societies have for decades played lead roles in supporting mathematical biology education. These societies organize conferences, provide funds, catalyze networking, and contribute to the development of educational materials. Given the opportunity of this special issue of the Bulletin of Mathematical Biology, the authors of this article ask: What more can societies be doing to support the education and development of new and existing mathematical biologists? What are societies doing well, and what novel approaches should they consider? How can funds, time, and other resources best be allocated to ensure the long-term prosperity of mathematical biology as a discipline?

Before addressing these questions, this article provides an overview of the roles of four professional societies: the Society for Mathematical Biology (SMB), the Symposium on Biomathematics and Ecology Education and Research (BEER), the Mathematical Association of America (MAA) along with its Special Interest Group in Mathematical and Computational Biology (BIO SIGMAA), and the Society for Industrial and Applied Mathematics (SIAM) including its Life Sciences activity group (SIAG-LS). Summary information on these societies appears in Table 1. We acknowledge that there are additional societies, such as the American Mathematical Society, that offer activities that may be of interest to those involved in mathematical biology education, yet we restrict our focus to those for which biology is central to the existence of the society or of a specific subgroup of the society. Similarly, we recognize that there are other organizations that provide resources related to mathematical biology education, but these are outside the scope of this article. Indeed, other articles in this special issue will discuss the roles of grant-supported groups such as QUBES, BioQUEST, Math Bench, and the Intercollegiate Biomathematics Alliance (IBA), as well as national institutes such as the National Institute for Mathematical Biology Synthesis (NIMBioS) and the Mathematical and Theoretical Biology Institute (MTBI).

We take a long view regarding our focal societies and mathematical biology education. Each exists within a continuum of advancement and assessment of educational choices, and each can be a leader in innovation for the education of future mathematical biologists. We also take a broad view of education, encompassing undergraduates, graduate students, post-doctoral researchers, and faculty, all of whom are learning and/or teaching in this interdisciplinary and fast-evolving field.

Organized discussion and planning regarding educating mathematical biologists extends back at least as far as the 1961 conference at Western Carolina

Society (Subgroup)	Full Name	Mission/Focus
SMB smb.org	The Society for Mathematical Biology	SMB promotes "the development and dissemination of research and education at the interface between the mathematical and biological sciences. It does so through its meetings, awards, and publications. The Society serves a diverse community of researchers and educators in academia, in industry, and government agencies throughout the world." [14]
BEER symposium.beer	Symposium on Biomathematics and Ecology Education and Research	The BEER Symposium gathers mathematics and biology researchers, educators, professionals, and students for a friendly exchange of ideas, networking, and dissemination of knowledge.
MAA (BIO SIGMAA) maa.org	The Mathematical Association of America (Special Interest Group on Mathematical and Computational Biology)	"The focus of BIO SIGMAA is on the pedagogy of mathematical and computational biology at the undergraduate level. This includes the support of curriculum development, faculty development, and undergraduate research in those fields." [3]
SIAM (SIAG-LS) siam.org	The Society for Industrial and Applied Mathematics (Activity Group on Life Sciences)	The Life Sciences activity group "...was established to foster the application of mathematics to the life sciences and research in mathematics that leads to new methods and techniques useful in the life sciences." [13]

Table 1 Four professional societies that link biology, mathematics, and education

College in Cullowhee, North Carolina [9] and is nicely documented in the MAA's curricular program report on mathematical biology [2]. In 2003 the report "BIO 2010: Transforming Undergraduate Education for Future Research Biologists" [10] called for recognition of changing biological methods, including computational and digital approaches, in the education of undergraduate students. The 2005 compilation "Math & Bio 2010: Linking Undergraduate Disciplines" [16] explicitly called for the academic disciplines of mathematics, computer science, and biology to work together, providing interdisciplinary experiences for their students. In 2009, recommendations [1] for medical college entry requirements shifted significantly, based on the advice of the Associa-

tion of American Medical Colleges and the Howard Hughes Medical Institute. Their goals for physicians included not just a strong science background, but also the skills and the mindset of curiosity to continually update their knowledge and integrate new findings into their careers. The 2015 Curriculum Guide of the MAA [2] provides both a historical overview and recommendations for courses, partnerships, and college and university resource allocation, while renewing and strengthening the call for cohesive undergraduate mathematical biology curriculum.

Intriguingly, some similar issues relating to mathematical biology education have persisted throughout these years of discussion. Working in an interdisciplinary field poses challenges that were recognized at the 1961 Cullowhee conference [9] and at many stages since. Biologists and mathematicians each have goals for their research and teaching, and mathematical biology goals may differ from those of both individual disciplines. Funding agencies, journal referees, and colleagues evaluating faculty for merit or tenure may use criteria that are unclear or at odds with the needs of interdisciplinary work—where interdisciplinary work addresses not just traditional research, but also how to educate at the interface of disciplines [4,6,11]. Mathematical biology programs do not incorporate an agreed-upon set of courses, research experiences, or order in which to deliver them. A burst of support for mathematical biology education can lead to valuable developments in course and curriculum design, but because research focus and direction can change in many realms—for mathematicians, computer scientists, biologists, researchers explicitly working in interdisciplinary programs, and others needed for this work—courses and curriculum can become out of date relatively rapidly, unless they are designed to include ongoing collaboration [8]. These challenges exist in realms beyond the professional societies, yet the societies are and should continue to be advocates for addressing these issues and sources for innovative solutions.

The following four sections focus individually on SMB, BEER, MAA/BIO SIGMAA, and SIAM, covering both historical perspectives and current activities and opportunities. These are followed by a concluding section in which we make comparisons across all four societies and offer our perspectives on how these societies can best support mathematical biology education in upcoming years. Our suggestions include steps related to the collection, dissemination, and exchange of data, ideas, and resources; the development and maintenance of structures such as mentoring systems, research communities, and summer schools; and the furnishing of incentives and visibility for efforts related to mathematical biology education.

2 SMB

The Society for Mathematical Biology (SMB), founded in 1973, has long bridged different worlds. Most obviously, SMB connects mathematics and biology through its meetings, grants, awards, web presence, and publications. In addition, SMB has a decades-long record of strengthening the ties between re-

search and education, with SMB members recognizing that professional-level research relies on outstanding education throughout the student years and continuing into career development. This section details the contributions of SMB to education and concludes with a call for further strengthening and supporting SMB's dedication to mathematical biology education.

Contributions of SMB to education can be grouped into four categories: Representation, Mentoring, Awards and Grants, and Minisymposia. Representation refers to the multiple ways SMB members use official structures to advocate distinctly for mathematical biology education as a scholarly goal. The Education Committee, its successor the Education Subgroup, and their members who serve on the SMB Board of Directors are the most visible representatives for education. Mentoring describes the unique, vertically-integrated SMB mentoring program, which has existed and evolved for several years while remaining a vibrant resource for students and for professionals who are now in the position to educate others. Awards and Grants include named awards supporting and rewarding education efforts, the accompanying plenary talks to honor awardees, and grants to support students and researchers in attending and organizing conferences. Minisymposia are a core and ongoing opportunity for conversation, presentation of ideas, and support for math biology educators to attend conferences. More details on each of these appear below.

2.1 Representation

Education as a focus of research and collaboration has been propelled forward by a subset of SMB members who have dedicated their time, creativity, and energy. For decades, the Education Committee provided these members a home through gatherings, meals, and minisymposium sessions at SMB Annual Meetings, along with an email list to promote further communication. This committee promoted education as a high priority for all members of SMB and for our students. Simultaneously, the Education Committee welcomed new SMB members with open arms and involved us with the workings of the Society while we were establishing our careers. This is an outstanding example of a low-risk, high-reward mechanism that a society can offer to encourage members to become involved! It also exemplifies that education does not refer only to training of students, but also to the ongoing development of faculty as they move through the stages of a career in mathematical biology.

In 2016, SMB changed structures to create Subgroups, and the Education Committee now exists as the Education Subgroup. The Education Subgroup receives SMB funding to financially support speakers, using these grants preferentially for junior faculty in need of funding support. By formally recognizing a Communications officer, this Subgroup emphasizes the pivotal role of communication in connecting mathematicians, biologists, interdisciplinary researchers, students, faculty, and more. For years, the Education Committee/Subgroup has provided an Education Editor to the Bulletin of Mathematical Biology, SMB's flagship journal.

Another valuable aspect of Representation is the presence of education-focused members on the SMB Board of Directors. In many years, the Education Committee/Subgroup has had at least one representative on the Board, with the goal of keeping education and related issues as a focal point of Board conversations. Continued representation at the level of the Board, the active buy-in of multiple SMB presidents, and supporting a Committee/Subgroup dedicated both to bringing in and nurturing new talent and to providing consistent representation at other levels of SMB, have been key strategies to maintaining and growing the role of education at the interface of mathematics and biology.

2.2 Mentoring

Organizations that support mentoring acknowledge that learning about the profession, the acquisition of new skill sets, and additional training happen through many stages of a career. They also recognize the many stages at which researchers can influence students and other newcomers considering entering the field.

The SMB's mentoring program serves a distinctive role in multiple ways. Participants may work in mathematics, biology, a related field, or in an interdisciplinary program; while mentoring programs exist within mathematics, or within specific areas of biology, the SMB program successfully links disciplines. Additionally, the SMB mentoring program serves mathematical biologists at multiple levels of seniority, from students to post-docs to junior faculty and beyond. SMB encourages participants to take part as both mentor and mentee; that is, a single person may fill both roles in the same year. With this in mind, a post-doc, for instance, can gain experience as a mentor to a graduate student, while also learning as a mentee from a faculty member. Students may be paired with someone just a few years ahead of themselves, perhaps learning interview advice from a recent job seeker, or with someone more senior, who can provide long-term career suggestions. This vertically-integrated structure acknowledges that all of us can teach, and can learn, throughout our lives, and in this way the mentoring program helps our members educate each other about all sorts of aspects of mathematical biology and related careers. Additionally, mathematical biologists at many stages have the opportunity to lead courses, and the mentoring program is one place to ask questions and suggest advice to make us better educators.

Since 2007, the SMB mentoring program has conducted an early-career workshop, including a luncheon, a discussion, and practice developing the "elevator pitch" of a candidate's research program, to help job candidates be able to best present themselves on the job market. Beginning in 2019, SMB is expanding its mentoring program to be year-round. Interested participants may join a variety of small groups or pairs. Some emphasize writing or accountability. Others provide the opportunity to talk regularly with someone at a similar career stage, or to work with others at multiple career stages. SMB is

also producing webinars on topics such as paper writing, choosing a journal, and collaborating across disciplines [15].

2.3 Awards and Grants

First awarded in 2017, the John Jungck Prize for Excellence in Education honors "significant contributions to education in mathematical biology, including a distinguished record of excellence in classroom instruction, mentorship of research scientists at any level, development of novel educational methods, materials, or programs, promotion of scientific outreach efforts to the public or to youth, a track record of attracting new students to the field of mathematical biology, or creation of an environment exceptionally conducive to education in mathematical biology." The award provides a cash prize, and the recipient gives a plenary talk at the SMB Annual Meeting. This award is a wonderful opportunity to honor John Jungck, who has been a leading force in mathematical biology education throughout his career. It also provides an outstanding occasion for the entire SMB community to gather around a speaker emphasizing the role of education in developing our students, and ourselves, as mathematical biologists.

SMB additionally provides grants to promote the growth of mathematical biology through travel, conferences, and outreach. The Landahl Grant encourages attendance at the SMB Annual Meeting. Education and outreach grants support SMB member participation in events for the public, such as the USA Science and Engineering Festival. Meeting grants finance stand-alone meetings, as well as workshops focused on mathematical biology that occur within larger conferences. International grants provide resources that support the organization of mathematical biology meetings and courses in countries experiencing financial need. When these grants support the travel of individuals, preference is typically given to junior scientists or those with particular financial need. Some of these grants specify an emphasis on education or outreach, and all are able to be used by mathematical biologists as we learn more about this career and/or as we think about educating others in mathematical biology.

2.4 Minisymposia

Minisymposia are a fundamental component of education about mathematical biology. For more than twenty years, at least one minisymposium on education has taken place at almost every SMB Annual Meeting. Audiences typically fill, even overflow, the room. Minisymposia serve the core advocates of mathematical biology education, while remaining accessible to anyone who drops in, as many people do while thinking about upcoming teaching assignments. Education sessions are distinguished by the way they mix together mathematical biologists with a variety of research specialties: all of us can gather to think about how best to attract and train students.

Conference talks on education are subject to unique circumstances, as many home institutions or other funders do not recognize education talks in the same way as they recognize more traditional research talks. They may not provide travel funding for these talks, or they may not weigh them as heavily when determining merit pay. Therefore SMB has, in most years, permitted participants to give an education talk as well as a research talk, even when conference attendees were otherwise restricted to giving a single talk. Unless or until funding changes in the future, this is a wise and valuable way to encourage education talks at SMB meetings.

3 BEER

The Symposium on Biomathematics and Ecology Education and Research (from here on referred to as BEER) grew out of a biomathematics workshop that the main organizer Olcay Akman attended in 2007. Akman's desire to continue the dialogue with a wider community at his own institution provided the inspiration for an informal gathering of researchers and educators in mathematical biology. The first such attempt gave birth to the inaugural BEER symposium, organized by Olcay Akman and Timothy Comar in 2008, which was held at Illinois State University, Normal, IL. The meeting hosted 30 attendees from across the U.S. and Canada. The attendees enjoyed a day of 10 oral presentations in one session, followed by a rich banquet where complimentary beer was served. From this humble origin, the conference has been held annually for twelve years. Due to its friendly and inclusive philosophy, it has expanded to become much larger, reaching nearly 200 worldwide participants attending talks in 8 parallel sessions as well as a poster session over a three-day period. Although it is an annual meeting, collaborations that are initiated at the meeting give birth to countless publications and further research, which are not unlike the functions of a typical professional society. Furthermore another unique aspect of the BEER Symposium is its close relationship with the journal *Letters in Biomathematics* where the participants of the BEER Symposium are provided with a continuing platform to disseminate their education or research focused work internationally.

Several defining aspects of BEER include:

- equal commitment to research and education focused work,
- allowing high-level involvement of faculty, post-doctoral researchers, graduate, and undergraduate students, as well as members from relevant industries with equal time allotments for all categories of speakers,
- multiple organized social events, such as a poster session reception and the traditional faculty versus students soccer match, designed to create an academically inclusive atmosphere where the participants can network, share ideas, and build friendships,
- fully refereed proceedings that welcome dissemination of work from all participants,

- regularly moving the geographical location of the meeting, which facilitates greater variety of participation, based on pre-determined regions,
- inviting participants from other community organizations, such as QUBES and BIO SIGMAA,
- federal/state funding and private/industrial sponsorships that help to keep attendance affordable for all participants.

Above all, the consistent success of the meetings is reflective of painstakingly-detailed planning efforts, which result in a high level of repeat participation. The contribution of BEER Symposia to the state of knowledge in mathematical biology is multifaceted. Over the last twelve years, clear and visible strengths of the conference have consistently emerged: the enabling of a productive dialog between members of mathematical and biological sciences who share an interest in both research and education, and the publication of the conference Proceedings. Past BEER Symposia are responsible for several ongoing collaborative projects for participants with diverse backgrounds. The contribution of the BEER Symposia to the main organizers' research and education agendas provides an illustration of the ongoing, significant professional benefits that many BEER attendees experience. The conference has also been, simply put, fun to attend. Attendees leave with renewed and strengthened professional relationships that transcend geography and discipline. The publication of the Proceedings in the past several years has enabled increased dissemination of the research presented at BEER to reach a much wider audience and help advance the state of knowledge in biomathematics. Moreover, metrics indicating success of BEER include:

- high-profile presentations delivered by prominent keynote speakers as well as well-respected plenary speakers,
- increased participation from faculty, post-doctoral researchers, graduate, and undergraduate students,
- steadily increasing participation from women, minorities, and under-represented groups,
- consistently high level of participation from both research and education communities,
- increased participation in BEER research contests,
- increasing level of submissions to Proceedings of the BEER Symposia.

Future plans for BEER include extending the meeting an additional day to allow for increasing number of submissions, designating an e-session, which will allow select participants to present remotely, and streaming the sessions, which will certainly enhance the impact and the quality of the upcoming meetings.

In summary, the BEER Symposium, which started as a modest conference in mathematical biology has evolved to become a subculture that is known by its nurturing, inclusive, and friendly environment. It has become one of the very few meetings where the repeat participation is extraordinarily high. The

BEER Symposium's unique combination of educational and recreational activities such as a traditional student versus faculty soccer match, a happy hour, among others are the defining factors for the meeting to be widely considered as a society in the field.

4 MAA and BIO SIGMAA

The Mathematical Association of American (MAA) is the leading professional organization for mathematicians dedicated to collegiate mathematics. As such, the MAA, in collaboration with other professional societies, has played a key role in the integration of mathematics and biology at the undergraduate level. The MAA's contributions include the "Math & Bio 2010" report [16], the sponsorship of many professional development workshops, short courses at national professional meetings, contributed paper sessions, and the formation and support of the Special Interest Group of the MAA in Mathematical and Computational Biology, which subsequently has taken the lead for promoting collaboration between the mathematical and biological communities, particularly in terms of undergraduate education, for the MAA.

4.1 Historical Involvement of the MAA

In 2003, the MAA collaborated with the National Science Foundation Division of Undergraduate Education, the National Institute of General Medical Sciences (NIGMS), and the American Association for the Advancement of Science (AAAS) on the project "Meeting the Challenges: Education across the Biological, Mathematical, and Computer Sciences." This project brought together leaders from these disciplines to discuss the strengthening of interdisciplinary activities between mathematics and biology education. The kick-off meeting of this project led to the 2005 MAA volume, Math & Bio 2010 [16]. As the "Meeting the Challenges" project was in preparation, the National Research Council published Bio 2010: Transforming Undergraduate Education for Future Research Biologists [10], which provided a call for re-envisioning how STEM disciplines are presented to life science students. The MAA volume can be seen as a partial response to Bio 2010 [16]. After the kick-off meeting, John Jungck organized the short course, "Reading the Book of Life: How Bioinformatics Makes Sense of Molecular Messages," at MathFest 2003. The MAA Subcommittee of the Committee on the Undergraduate Program in Mathematics (CUPM) on Mathematics Across the Disciplines (MAD) organized Themed Contributed Paper Sessions on mathematics and biology at MathFest 2004 and the 2005 Joint Mathematics Meetings. In 2007 the Annual Meeting of the Society for Mathematical Biology overlapped with MathFest, which created an opportunity for additional exposure to mathematical biology for the greater MAA community. In 2015, the MAA published its most recent CUPM Curriculum Guide, which, for the first time, included recommendations for mathematical biology curricula [2]. This report is currently under revision.

For the first decade and a half of the twenty-first century, the MAA ran week-long professional development workshops through the Professional Enhancement Program (PREP), which was supported with funding from the NSF DUE. Fortunately, there were several that focused on the integration of mathematics and biology at the undergraduate level. There were a series of early workshops on creating materials that would serve both biology and mathematics students by integrating mathematics into biology courses and biology into mathematics courses. These early workshops from 2003 to 2007 were often held in conjunction with workshops run by the National Computational Science Institute (NCSI) for biology educators. In addition to the creation of materials, these workshops developed a dedicated community of mathematicians and biologists who were committed to improving educational and research opportunities at the juncture of the biological, mathematical, and computational sciences.

The community built over time through these workshops was a key factor in the eventual founding of the MAA Special Interest Group in Mathematical and Computational Biology (BIO SIGMAA). Moreover, connections made at these and later workshops led to the creation of the BEER and formed the kernel of the BEER community, which has become another venue welcoming to those interested in mathematical and computational biology education and student research. Additional PREP workshops in 2010, 2011, and 2013 focused on using mathematical and computational techniques outside of calculus to address problems in biology for classroom activities and student research projects. Other successful PREP workshops in the area of mathematical biology education focused on the development of student research projects and on content and course design for calculus courses for biology students. A key lesson to take from the success of these intense and often repeated, week-long, residential workshops is that they were central in gathering both critical mass and energy to forge an ongoing community of mathematicians and biologists dedicated to fostering meaningful educational and research opportunities for undergraduates at the intersection of mathematics and biology.

4.2 BIO SIGMAA

The MAA Special Interest Group in Mathematical and Computational Biology (BIO SIGMAA), formed in 2006, has become the primary community within the MAA that promotes the integration of mathematics and biology at the undergraduate level. The focus of BIO SIGMAA is on the pedagogy of mathematical and computational biology at the undergraduate level. This includes the support of curriculum development, faculty development, and undergraduate research in those fields. The purpose of BIO SIGMAA is to promote those activities that will enhance the exchange of ideas and access to educational opportunities among undergraduates and undergraduate faculty in the fields of mathematical and computational biology [3]. Since its inception, BIO SIGMAA continues to serve its purpose through the support of ac-

tivities within and beyond the MAA. BIO SIGMAA has regularly sponsored Themed Contributed Paper Sessions on undergraduate mathematical biology education at the Joint Mathematics Meetings and MathFest. These have been focal points for BIO SIGMAA members and the greater MAA community to network and disseminate their work in undergraduate mathematical biology education and student research. The first of these sessions took place at the 2007 Joint Mathematics Meetings. This session subsequently led to a 2008 issue of PRIMUS (Problems, Resources, and Issues in Mathematics Undergraduate Studies) dedicated to undergraduate mathematical biology [7], and subsequently the 2013 MAA Notes Volume, Undergraduate Mathematics for the Life Sciences: Models, Processes, and Directions [8]. Recent sessions are leading to another forthcoming issue of PRIMUS. These sessions have proved to be fruitful avenues for professional scholarship among its participants and dissemination to the wider community.

In addition to the Themed Contributed Paper Sessions, BIO SIGMAA engages in other activities to promote mathematical and computational biology at national meetings. It sponsors an invited speaker at its annual business meeting and organizes an Invited Paper Session focusing on current research trends in mathematical and computational biology. BIO SIGMAA sponsored a short course at MathFest 2011 on trends in mathematical biology. The focus of the short course was to introduce participants to modern applications of mathematics to biology so that faculty could integrate these biological applications into the undergraduate mathematics program.

BIO SIGMAA's commitment to undergraduate research in mathematical biology includes coordination of the Janet Anderson Prize, which has been awarded each summer at MathFest since 2007. Early on, the BIO SIGMAA endorsed a conference called TIMBER (The Institute for Mathematical Biology Education and Research) on undergraduate research in mathematical biology. Several of the Themed Contributed Paper Sessions at MathFest sponsored by BIO SIGMAA have been focused on undergraduate research projects.

BIO SIGMAA is connected with other societies dedicated to the integration of mathematics and biology at the undergraduate level. One of these is QUBES [12]. Since 2016, BIO SIGMAA has sponsored an invited speaker focusing on education in mathematical biology at BEER Symposium.

5 SIAM and SIAG-LS

The Society for Industrial and Applied Mathematics, or SIAM, is a nonprofit organization, started in 1952, which stands as the premier international applied mathematics society. SIAM's mission statement emphasizes the development and dissemination of mathematical knowledge and techniques that could be helpful to professionals seeking to use mathematics in a wide range of application areas. Thus, its emphasis on education has had a practical orientation, focusing on training a workforce and disseminating cutting edge research developments. The latter is done in part via the publication of journals and books

across a variety of areas of applied mathematics. Although SIAM currently does not have a journal focusing on mathematics applied to the life sciences, many articles involving applications to biological systems appear regularly in a number of SIAM journals. The most general SIAM journal is the *SIAM Review*, which includes articles that aim to educate the readership about new topics in applied mathematics but are usually written for a research audience rather than for classroom use. Beyond its journals, SIAM's publications include textbooks, some of which are specific or related to mathematical biology (e.g. [5]), and *SIAM Review* also includes book reviews, some of which deal with textbooks. SIAM also publishes a regular newsletter, *SIAM News*, which has often included brief articles about research developments involving SIAM members who apply quantitative approaches to biological systems.

SIAM also supports a range of SIAGs, or special interest activity groups, including a SIAG on the Life Sciences (SIAG-LS) that, like most of the SIAGs, holds a biennial scientific conference. The first SIAM Conference on the Life Sciences took place in 2002. These meetings share SIAM's emphasis on research-level developments, networking, and bringing together researchers from different fields with common interests. Most of the talks at the meeting focus on research developments; recent conferences have included a small number of mini-tutorials aimed at researchers at all levels, not just students. Historically, the Conference on the Life Sciences has not included dedicated sessions related to mathematical biology education, although there is not a policy to preclude such sessions at future conferences. In addition to talks, the Life Sciences conference also includes a poster session with student prizes, which represents an excellent forum for early-career researchers including graduate students, as well as precocious undergraduates, to present their results.

The primary other SIAM meetings that could naturally include discussion of mathematical biology education topics are the SIAM Annual Meeting, which includes activities in all areas under the SIAM umbrella, and the biennial meeting of SIAM's Applied Math Education Activity Group (SIAG-AME), which first occurred in 2016. Session topics at the SIAG-AME meeting or run by group members at the SIAM Annual Meeting have included mathematical modeling, incorporating data into the undergrad math curriculum, career preparation for students, and research- and project-based education and opportunities for undergraduates. The SIAG-AME group also aims to provide professional development opportunities for teachers and a repository of relevant educational materials. Clearly the group's activities could include mathematical biology components, if members chose to organize them, but to date this potential has not been significantly realized.

SIAM has a significant web presence (www.siam.org) that includes a substantial range of educational materials. Most of the educational directions deal with applied mathematics in a broad sense, with a strong emphasis on mathematical modeling across all scientific areas, including but without special accentuation on biology. For example, SIAM's website includes a "Thinking of a career in applied math?" page with a link to a downloadable "CAREERS in applied mathematics" guide. This guide lists close to 100 job titles, a few of

which relate to the life sciences (e.g., biostatistician, pharmacokineticist); similarly, only a small minority of the professional applied mathematicians who are highlighted in the guide do work with a biological component. Interestingly, SIAM runs an annual Gene Golub SIAM Summer School aimed at graduate students. This program relies on organizers from the SIAM community, who apply to hold a school on a particular mathematical theme, such that topics vary from year to year; so far, none of the summer schools has had a significant biological component, but this forum could be used to run graduate-level educational programs in mathematical biology in future summers. Finally, SIAM offers free or significantly discounted memberships to students and supports a robust stable of student chapters, which student leaders could use as a staging ground for events relating to mathematical biology if they chose to do so.

In summary, SIAM represents a valuable resource for students interested in mathematical biology by supporting local student chapters and by offering print and in-person forums for dissemination of research as well as opportunities for networking with other professionals, mostly in the general realm of applied mathematics but with a specific Life Sciences activity group and conference. SIAM's career guides would be of interest to students and educators alike; these span all areas of applied mathematics with little content on biological directions currently, and expansions of the biological aspects of these materials could be valuable for the mathematical biology community. SIAM offers extensive educational materials that could be of great interest to educators. The significant resources related to mathematical modeling could be helpful for guiding the education of students in mathematical biology, but for the most part, it would be up to the individual educator to adapt the materials in this direction. In theory, there is strong potential for an expanded role of SIAM in mathematical biology education; this expansion would largely need to be driven by a push from members to organize relevant events at SIAM meetings or through their local SIAM student chapters, but the SIAM leadership could also contribute, for example by promoting participation of SIAG-LS members in SIAG-AME activities or running these two conferences together in the near future.

6 Discussion

The four societies profiled in this article share many common features, yet serve distinctive groups of educators and students. In this discussion section, we clarify many of the similarities and differences among the societies, while summarizing their varied contributions to mathematical biology education. We then suggest directions in which these societies can support and advocate for continued attention to education at all levels of mathematical biology.

A clear similarity across the societies is that each hosts a meeting on a regular basis: once per year or once every two years. In some cases, these meetings intersect: SIAM Life Sciences and SMB co-hosted a meeting in 2006; SMB and MAA held overlapping meetings in 2007; SIAM's activity group on Applied

Mathematics Education (SIAG-AME) will be part of MAA's summer meeting in 2020; BEER has designated a BIO SIGMAA speaker at each meeting since 2016. Each society supports publishing: SIAM and MAA produce books, and all four societies publish journals and/or conference proceedings; each society has published works in the category of education. All of these societies are very much member-driven. Members serve on organizing committees for meetings and determine the specific activities that will take place. In this sense, individuals interested in mathematical biology education have opportunities to promote relevant topics in the context of all of these societies' activities.

SMB and BEER are fundamentally mathematical biology societies, while MAA and SIAM are broader institutions that have developed specific subgroups, BIO SIGMAA and the SIAG-LS, with biological emphases. Although a significant portion of BIO SIGMAA activities focus on education, educational topics under the SIAM umbrella largely fall under a separate activity group from the SIAG-LS, namely the SIAG-AME. While students take part in meetings for each society, participation across meetings does differ; were we to list societies on a continuum between undergraduate and graduate student representation at conferences, MAA would lie more on the undergraduate side, BEER would sit approximately in the middle, and SMB and SIAM would be more on the graduate student side. SMB, BIO SIGMAA, and SIAG-LS give prizes with educational aspects, SMB's to honor mathematical biology education by a faculty member and those of BIO SIGMAA and SIAG-LS to recognize student research. Finally, a key, distinctive feature of the MAA has been its support for various publications that specifically deal with undergraduate mathematical biology education (such as [2,8,16]). In an alternative publication domain, SMB supports a journal, *Bulletin of Mathematical Biology*, which according to its "Aims and scope" statement publishes "articles that discuss ideas, methods, tools, and activities to enhance research and education, both inside and outside the classroom"; this special issue fits under this heading. SIAM, on the other hand, lacks a life sciences journal but does publish an Education section in its flagship *SIAM Review*, which does occasionally include articles relating to mathematical biology (e.g., [17]).

Moving forward, these societies all have the opportunity to shape the nature of the scholarly work of mathematical biology education, through meetings, plenary speaker selection, prizes, grants, public statements, and publishing choices. An important motivation to do this is that education is a primary component of interdisciplinary scholarship. As mentioned in earlier sections, the very nature of interdisciplinary scholarship encompasses different goals than the goals of more traditional research. Recent articles on interdisciplinarity [6,11] tell us that traditional research tends to focus on discovery—for instance, discovering new mathematics—whereas interdisciplinary scholarship is best served by encompassing discovery, integration, application, and teaching. Expanding scholarly reward systems to incorporate these areas is not a new idea [4] and professional societies have their own reward systems that can prioritize all four areas. To specify: professional societies can provide funding, infrastructure, prizes, news stories, and platforms for sharing developments

at conferences and online. Examples, existing and aspirational, include the following, which are all important and are not ordered by priority:

- maintain and expand awards recognizing achievement in education, such as SMB's John Jungck Prize for Excellence in Education;
- continue and enhance the publication of educational materials and materials focusing on applications of mathematical biology, possibly to include developing or expanding specific educational sections within journals;
- provide funds and infrastructure for the development and dissemination of Open Educational Resources, thereby making materials affordable and accessible for far more people;
- visibly and financially sponsor Open Educational Resources made available through other groups, such as QUBES, thereby supporting such efforts overall while also connecting society members with these resources;
- gather data for assessment of existing educational programs;
- continue to provide structures, such as mentoring systems and long-term curriculum-focused committees, that maintain and promote progress in curriculum development and education at all levels;
- host workshops or other opportunities for sharing curricula, either through existing programs such as SIAM's Gene Golub Summer School or through the development of new ones;
- provide additional cross-fertilization opportunities, such as overlapping conferences and social media connections, so that members of one society can readily learn about and access the educational work of other societies;
- promote more activities to educate members about cross-disciplinary trends as they are occurring, a current example being the roles of machine learning and increased reliance on data in biological research;
- support mentored research experiences, such as the Mathematics Research Communities of the American Mathematical Society, that provide research-oriented educational opportunities specifically in mathematical biology.

We conclude this article by encouraging all of us, as individuals and as members of professional societies, to work toward putting these ideas into action. Mathematical biology is no longer a new realm, yet its future scope and implementation remain uncertain. One reason is that the specific research topics in mathematical biology continually evolve, and our educational focus must evolve accordingly as well. Also crucial is that the ability for researchers, educators, and students to succeed in mathematical biology is closely linked with academia-wide support for interdisciplinary scholarly efforts. We must recognize that interdisciplinary work encompasses collaboration, communication, education, and application of existing ideas to new fields, and that these are all central to progress. Professional societies can prioritize these through education-focused prizes, awards, grants, plenary speakers, social media posts, minisymposium topics, and news stories. Professional societies can further call for major funding agencies, colleges, and universities to revisit their priorities regarding grant funding criteria, hiring, reappointment, tenure, promotion, and merit pay: rather than focus so heavily on "discovery", these should all

support education, application, and integration as well. As individuals, we should participate actively in our professional societies, building community, leading or otherwise participating in new initiatives, and serving as mentors and mentees, educating ourselves and each other so that we continue to nurture students and professionals at all levels. As we all shift our priorities in ways that help our community grow and that actively welcome new students and professionals—all of which fall under the title of "education" as we see it—we build the entire realm of mathematical biology and strengthen its foundations for the future.

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